4th International Workshop on B physics and CP violation
Ise-Shima, Japan, February 19 - 23, 2001

**LOW ENERGY SUPERSYMMETRY AND THE TEVATRON BOTTOM QUARK CROSS SECTION**

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February 23, 2001

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hep-ph/0012001
http://gate.hep.anl.gov/berger/seminars/BCP4.ps
1. Motivation and Constraints

- Measured cross section for bottom quark production at hadron colliders exceeds the (central value of) predictions of next-to-leading order (NLO) QCD by about a factor of 2 [→ Fig.]

- NLO contributions are large, and it is not excluded that further NNLO effects may do the trick, but ...

- Longstanding discrepancy has resisted satisfactory resolution within the SM → room for new physics?

- Propose a possible explanation within the context of the minimal supersymmetric standard model (MSSM):
  - assume existence of a light color-octet, spin-1/2 gluino (\(\tilde{g}\))
  - and a light color-triplet spin-0 bottom squark (\(\tilde{b}\)):

\[
p + \bar{p} \rightarrow \tilde{g} + \tilde{g} + X,
\]

\[
\tilde{g} \rightarrow b + \bar{b}
\]

- Masses constrained by "fit" to the hadron collider data:
  - \(m_{\tilde{g}} \approx 12\) to 16 GeV; \(m_{\tilde{b}} \approx 2\) to 5.5 GeV

- \(\tilde{b}\) is long-lived on the scale of colliders or it decays hadronically (via R-parity violation?)

INTEGRATED TRANSVERSE MOMENTUM SPECTRUM FOR $b$ QUARKS

$p\bar{p} \rightarrow bX$, $\sqrt{s}=1.8$ TeV, $|y|<1$

CDF

$J/\psi$

$\psi(2S)$

$\nu\nu$

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Differential $b$-jet Transverse Momentum Distribution

$pp \rightarrow bX$, $\sqrt{s}=1.8$ TeV, $|\eta|<1.0$

- **DØ Data**
- **NLO QCD(•), MRSA/**
- **Theoretical Uncertainty**


DØ Preliminary
(Errors have correlations)
LEP Constraints on Bottom Squark Couplings
(Carena, Heinemeyer, Wagner, and Weiglein, hep-ph/0008023)

- Light $\tilde{b}$ would be ruled out by LEP1 data unless its coupling to the $Z$ boson is small.

- Squark couplings to the $Z$ depend on the mixing angle $\theta_{\tilde{b}}$.

- Let $\sin\theta_{\tilde{b}} = s_{\tilde{b}}$ be the left-handed component of the lightest $\tilde{b}$ mass eigenstate; $s_W^2 = \sin^2 \theta_W$.

- Coupling $g_{Z\tilde{b}_1\tilde{b}_1} \sim [T_3 s_{\tilde{b}}^2 - Q_{\tilde{b}} s_W^2]$ ($T_3 = -1/2; Q_{\tilde{b}} = -1/3$).

- Coupling to $Z$ vanishes for $s_{\tilde{b}}^2 \sim 1/6$.

- Thus, if the light bottom squark is an appropriate mixture of left-handed and right-handed bottom squarks, tree-level coupling to the $Z$ can be made small.

- $Z - \tilde{b}_1 - \tilde{b}_2$, $Z - \tilde{b}_2 - \tilde{b}_2$ couplings survive in this limit.

- Require $m_{\tilde{b}_2} > 200$ GeV to avoid $e^+e^- \rightarrow Z^* \rightarrow \tilde{b}_1 + \tilde{b}_2$. 
Further Considerations

- For a small range of values of $s^*_b$, $Z$-peak observables $\Gamma_Z$, $R_c$, $R_\ell$, $R_b$, $A^b$, $A^b_{FB}$ are fit about as well as in the SM.

- A light $\tilde{b}$ with some $\tilde{b}_L$ component will contribute to $\Delta \rho$ ($T$ parameter), depending on the $\tilde{t}$ sector; constrains the top squark mass to be light ($m_{\tilde{t}} \sim m_t$).

- Exclusion by CLEO of a light $\tilde{b}$ with mass 3.5 to 4.5 GeV does not apply since their analysis focuses on $\tilde{b} \rightarrow c\ell\bar{\nu}$ and $\tilde{b} \rightarrow c\ell$.

- ALEPH LEP analysis of 4 jet events excludes a $\tilde{g}$ with $m_{\tilde{g}} < 6.5$ GeV, but not gluinos in the mass range of interest to us. Light $\tilde{b}$ is not excluded by 4 jet analysis (Z. Phys C76, 1 (1997)).

- Dedes and Dreiner use the renormalization group method to argue that the existence of a light $\tilde{b}$ goes hand-in-hand with a comparatively light $\tilde{g}$, $m_{\tilde{g}} \sim 10$ GeV.

(hep-ph/0009001)
2. Production Processes

- Pair production of $Q\bar{Q} = b\bar{b}, \tilde{g}\tilde{g}$ via $gg$ scattering in LO QCD:

- Second set of LO diagrams for $q\bar{q}$ initial state, but $gg$ scattering dominates at Tevatron energies for the masses we consider. All contributions are included in our numerical calculations.

- QCD NLO calculation of $b$ cross section with CTEQ4M parton densities; renormalization/factorization scale $\mu = \sqrt{m_b^2 + p_{Tb}^2}$; SUSY-QCD contributions to $b$ production are not included – not available and expected to be small.

- Fully differential NLO calculation of $\tilde{g}$ pair production and decay $\tilde{g} \rightarrow b + \bar{b}$ does not exist; $\tilde{g}$ contribution computed at LO; $\mu = \sqrt{m_\tilde{g}^2 + p_{T\tilde{g}}^2}$; and multiplied by an overall NLO enhancement ($K$) factor.

- $g + b \rightarrow \tilde{g} + \bar{b}$ contributes less than 2% of $\sigma_{b\bar{b}}^{\text{qcd}}$. 
3. Differential Cross Section

\[
\sigma_b(p_T) \propto \frac{1}{p_T^{\text{min}}} (\text{nb})
\]

\[
\sqrt{s} = 1.8 \text{ TeV}
\]

- Values of \(m_{\tilde{g}} \approx 12 \) to 16 GeV produce \( p_{Tb} \) spectra that are enhanced near \( p_{Tb}^{\text{min}} \approx m_{\tilde{g}} \) where data deviate most from pure QCD; light \( \tilde{g} \) necessary to obtain a \( b \) cross section comparable to the pure QCD rate.

- The rapidity distribution of the \( b \)'s and the azimuthal angular distributions \( \Delta \phi \) between the final \( b \)'s are very similar after \( p_T \) selections in the SUSY and pure QCD cases.
Choice of $m_\tau$ impacts the kinematics of the $b$; large values of $m_\tau$ reduce the cross section and result in $p_{Tb}$ spectra that agree less well with data; choices of $m_\tau$ and $m_b$ are coupled.
4. Ratio of Same-Sign to Opposite-Sign Leptons

- QCD processes produce $b\bar{b}$ pairs
- Majorana $\tilde{g}$ decays into $b$ and $\bar{b}$
- $\tilde{g}\tilde{g}$ pair production will generate $bb$ and $\bar{b}\bar{b}$ pairs as well as $b\bar{b}$ pairs $\rightarrow$ potential increase in same-sign lepton pairs, and apparent increased rate of $B\bar{B}$ mixing
- For highly relativistic $\tilde{g}$'s, $\tilde{g}$'s helicity is nearly the same as its chirality $\rightarrow$ selection of $\tilde{g}$'s with $p_T\tilde{g} \gg m_{\tilde{g}}$ reduces same sign $b$'s.
- Cuts chosen in Tevatron run I $\rightarrow$ principally unpolarized $\tilde{g}$'s and thus, at production, $N(bb + \bar{b}\bar{b}) \approx N(b\bar{b})$
- Analyze effect of the new SUSY contribution in terms of $\tilde{\chi}$
  - $\tilde{b} \rightarrow B^o, B_s, \Lambda_b, B^+$
    $\rightarrow \ell^+$, "right sign", with probability $1 - \tilde{\chi}$
    $\rightarrow \ell^-$, "wrong sign", with probability $\tilde{\chi}$
  - Define $LS$, same-sign lepton fraction
  - Conventional $b\bar{b}$ pair production
    $\rightarrow LS = 2\tilde{\chi}(1 - \tilde{\chi})$
- New expression
- **Definition:**

\[ G = \frac{\sigma_{\bar{g}g}}{\sigma_{QCD}} \]

- Ratio \( G \) is determined in the (cut) region of phase space where \( LS \) is measured; CDF: \( p_T > 6.5 \text{ GeV} \) and \( y_b \leq 1 \), both \( b \)'s

- Hadron collider experiments measure

\[ \bar{\chi}_{\text{eff}} = \frac{\bar{\chi}}{\sqrt{1+G}} + \frac{1}{2} \left[ 1 - \frac{1}{\sqrt{1+G}} \right] \]

- For \( m_{\bar{g}} = 14, 16 \text{ GeV} \), we compute \( G = 0.37, 0.28 \)

- Adopt average value from PDG: \( \bar{\chi} = 0.118 \pm 0.005 \)

- **Predict:**

\[ \bar{\chi}_{\text{eff}}^{\text{th}} = 0.17, m_{\bar{g}} = 14\text{GeV} \]

\[ \bar{\chi}_{\text{eff}}^{\text{th}} = 0.16, m_{\bar{g}} = 16\text{GeV} \]

- Large QCD theoretical uncertainties (scale dependence, no fully NLO calculation of \( \bar{g} \) pair production and decay):

\[ \delta \bar{\chi}_{\text{eff}} \approx \pm 0.02 \]

- CDF measurement is higher than the world average

(\text{PRD 55, 2546 (1997)}):
5. Other Implications and Remarks

5 a) Hadron Reactions

- Most clearcut expectation is pair production of like-sign $B$'s: $B^+B^+$ and $B^-B^-$

- Very precise measurement of $\bar{\chi}$ at run II is desirable; fraction of $b$'s from gluinos also changes with $p_{Tb}$ so there should be a change of $\bar{\chi}$ with the cut on $p_{Tb}$

- The $b$ jet from $\tilde{g}$ decay into $b\bar{b}$ will contain the $\tilde{b} \rightarrow$ unusual material in some fraction of the $b\bar{b}$ data sample from the $\tilde{b}$ in the $b$ jet

- Existence of light $\tilde{b}$'s means they will be pair-produced directly $\rightarrow$ slight increase ($< 1\%$) in the hadronic dijet rate

- Increased rate of $b$ production at HERA ($\gamma^* g \rightarrow b\bar{b}$) and in $\gamma\gamma \rightarrow b\bar{b}$ at LEP, but perhaps too small if current data are confirmed; NLO calculation and better parton densities of photons are needed.
5 b) \( \tilde{b} \) lifetime and observability

- Simple scaling from \( \mu \) or \( \tau \) lepton decay, \( \tau^{-1} \sim m_5 \), suggests \( \tau_\tilde{b} \sim 10^{-14} \) s (\( c \tau \approx 3 \mu \text{m} \)) for \( m_\tilde{b} = 3.5 \text{ GeV} \)

- But, R-parity conservation does not permit \( \tilde{b} \) decay unless there is an even lighter LSP

- Limits on baryon-number-violating R-parity-violating couplings \( \lambda'' \) are relatively weak for 3rd generation \( \tilde{q} \)'s: \( \lambda'' < 0.5 \) to 1 (Allanach Dedes Dreiner, PR D60, 075014 (1999))

- MSSM superpotential with baryon-number-violating R-parity-violation term

\[
W_{R_p} = \lambda''_{ijk} U^c_i D^c_j D^c_k
\]

- \( U^c_i \) and \( D^c_i \) are right-handed-quark singlet chiral superfields; \( i, j, k \) are generation indices

- Possible \( R_p \) decay channels are 123 : \( \tilde{b} \rightarrow u + s \), 213 : \( \tilde{b} \rightarrow c + d \), and 223 : \( \tilde{b} \rightarrow c + s \)

\[
\Gamma(\tilde{b} \rightarrow jj) = \frac{m_\tilde{b}}{2\pi} \sin^2 \theta_\tilde{b} \sum_{j<k} |\lambda''_{ij3}|^2
\]

- If \( m_\tilde{b} = 3.5 \text{ GeV} \), \( \Gamma(\tilde{b} \rightarrow ij) = 0.08|\lambda''_{ij3}|^2 \text{ GeV} \)

- Unless \( \lambda''_{ij3} \) is extremely small, the \( \tilde{b} \) will decay quickly and leave soft jets in the cone around the \( b \); jets with an extra \( e \) are possibly disfavored by CDF; detailed simulation is needed.
5 b) $\tilde{b}$ lifetime and observability, continued

- Suppose the $\tilde{b}$ is relatively "stable", what could happen?
  - $\tilde{b}$ picks up a light $\tilde{u}$ and becomes a $\tilde{B}^-$ "mesino" with $J = 1/2$, the superpartner of the $B$ meson, a hadron with mass $\sim 3$ to 7 GeV
  - The mesino is not a muon but could fake a heavy muon as it exits the muon chambers; $\Rightarrow$ extra "muons" in a fraction of the $b\bar{b}$ event sample, with tracks that left some trace in the hadron calorimeter?
  - The mesino has baryon number 0 but acts like a heavy $\bar{p}$ – perhaps detectable with a TOF detector in run II
  - Detailed analyses should be done at hadron colliders to verify what ranges of $\tilde{b}$ masses and lifetimes may be allowed/disfavored, similar to that done for $\tilde{g}$'s (c.f. Baer, Cheung, Gunion, PRD 59, 075002 (1999))
  - $\tilde{b}$-onia
  - $\tilde{b}$'s will be made in cosmic ray collisions or in particle detectors $\Rightarrow$ weird isotopes?
5 e) \( \alpha_S \)

- Global fit to all observables in the SM provides
  \[ \alpha_S(M_Z) \sim 0.119 \pm 0.006 \text{ under SM running} \]

- Light gluino and light bottom squark modify \( \alpha_S(M_Z) \)
determined by extrapolation from experiments at energies
below \( m_{\tilde{g}} \)

- \( \beta \) function of (SUSY) QCD:
  \[
  \beta = \frac{g^3}{16\pi^2} \left[ -11 + \frac{2}{3} n_f + \frac{1}{6} n_s + 2 \right]
  \]

- The QCD running of \( \alpha_s(Q) \) is slowed
  - \( \tilde{b} \) (color-triplet scalar) contributes little to the running
  - \( \tilde{g} \) (color octet fermion) much more significant

- Shift of 0.007 to \( \alpha_S(M_Z) \approx 0.125 \), within the range of
  uncertainty but towards the upper end

- **Separate issue** concerning \( \alpha_S \) is gauge-coupling
  unification: for gluinos of mass in the hundred GeV range,
  \( \alpha_S(M_Z) \) predicted from unification is \( > 0.13 \), but 15
  GeV gluinos reduce the value to \( \leq 0.127 \), in better
  agreement
Influence on Parton Densities

- Kinematic range in the \((x, Q^2)\) plane of data included in a typical global analysis of parton densities

- Slower running of \(\alpha_s(Q)\) means a slower evolution of parton densities at small \(x\), an effect that might be seen in HERA data for \(Q > m_Z\). Under investigation

- Presence of scalar \(\tilde{b}\) in the proton breaks the Callan-Gross relation and yields a non-zero leading-twist longitudinal structure function \(F_L(x, Q)\)
5 d) $R$ and Angular Distributions in $e^+e^- \rightarrow \text{jets}$

- Deviations of $R$ from SM expectations at large $\sqrt{s}$?

$$R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-}$$

- Scalars are produced in a $p$-wave coupled to the intermediate photon
  - Thresholds turn on slowly
  - Cross sections are small ($\sim 1/4$ a fermion of the same charge)

- Compared to "everything else" $\tilde{b}$ contributes

$$\left(\frac{1}{3}\right)^2 \frac{1}{4} \ versus \ 2 \left(\frac{2}{3}\right)^2 + 3 \left(\frac{1}{3}\right)^2$$

$$\frac{1}{36} \ versus \ \frac{11}{9}$$

- Data must be accurate to a few % to discriminate

- Angular distributions are potentially more powerful, $\sin^2\theta$ vs. $(1 + \cos^2\theta)$; data not inconsistent with a single pair of charge-1/3 squarks along with 5 flavors of $q\bar{q}$ pairs; $(1 + \alpha\cos^2\theta)$, with $\alpha \approx 0.92$
Could be seen as mesonic resonances in $\gamma\gamma$ reactions (i.e., $e^+e^- \rightarrow e^+e^- X$) and in $p\bar{p}$ formation, with masses in the 4 to 10 GeV range and $J^P = 0^+, 1^-, 2^+$, ... 

Could show up as narrow states in $\mu^+\mu^-$ invariant mass spectra at hadron colliders, between the $J/\psi$ and $\Upsilon$ 

At an $e^+e^-$ collider, the intermediate photon requires production of a $J^{PC} = 1^{--}$ state.

- Bound states of low mass squarks with $Q_{\tilde{q}} = 2/3$
  studied by Nappi with a potential model (Phys. Rev. D25, 84 (1982))
  * $\Gamma_\ell \sim 24$ eV
  * $\Gamma_h \sim 18$ keV
  * $\Gamma_{1S+\gamma} \sim 65$ keV

- The $1S$ state decays hadronically

- Because the leptonic decay widths are too small there are no bounds for $m_{\tilde{q}} > 3$ GeV, $Q_{\tilde{q}} = 2/3$

- For bottom squarks, the situation is stronger ($Q_{\tilde{q}} = -1/3$).
5f) Alternative Scenarios

- Suppose only the $\tilde{b}$ is light
  - Assume $\tilde{b}$ decay products (e.g., $\tau e$ via R-parity violation) are similar to those in $b$ decay
  - $\sigma_{\tilde{b}\tilde{b}} \approx \sigma_{bb}$ for $m_{\tilde{b}} \approx 3$ GeV
  - Fails: excess in $J/\Psi$ channel not produced, and $p_Tb$ spectrum not reproduced

- Light $\tilde{b}$ and light $\tilde{g}$, with $m_{\tilde{b}} + m_b > m_{\tilde{g}}$ but $m_b < m_{\tilde{b}} < m_{\tilde{g}}$
  - $\tilde{g} \rightarrow \tilde{b}s$ or $\tilde{g} \rightarrow \tilde{b}d$; $\tilde{b} \rightarrow b\tilde{\chi}^0$ (light $\tilde{\chi}^0$)
  - Requires FV coupling $\tilde{g} - \tilde{b} - s$ to suppress $\tilde{g} \rightarrow g\tilde{\chi}^0$
  - Killer: $\sigma(b + \bar{b} + E_T)$ much too large; excluded at run I
6. Summary

- There is room in the measured bottom quark production rate at hadron colliders for new physics
- We postulate the existence of light gluinos and light bottom squarks with 100% branching fraction $\tilde{g} \to b\bar{b}$
  - $m_{\tilde{g}} \approx 12$ to 16 GeV; $m_{\tilde{b}} \approx 2$ to 5.5 GeV
- Our SUSY scenario with $\sigma_{\tilde{g}\tilde{g}}/\sigma_{\text{QCD}} \sim 1/3$ helps to explain the magnitude and shape of the $b p_T$ distribution at the Tevatron
- $bb$ and $\bar{b}\bar{b}$ pair production predicted
  - Visible as a mismatch of $B^0$ oscillation parameters at the Tevatron and at $b$ factories
  - Tevatron run I $\chi$ data help constrain gluino mass
  - Should see $B^+B^+$ events at run II
- Search for $\tilde{b}$-onia
- $b$ cross sections at HERA and LEP ($\gamma\gamma \to b\bar{b}$) bear watching
- Interesting SUSY consequence: light $\tilde{t}$
- $h^0 \to \bar{b}b^*$ dominates: could modify Higgs bounds

http://gate.hep.anl.gov/berger/seminarsxBCP4.ps